

Effects of fire on cultural resources

Kevin C. Ryan

*Missoula fire Sciences Laboratory, U.S. Forest Service, Rocky Mountain Research
Station, 5775 US Highway 10 W., Missoula, MT, USA 59808, kryan@fs.fed.us*

Abstract

Cultural resources (CR) refer to the physical evidence of human occupations which archaeologist use to reconstruct the past. This includes the objects, locations, and landscapes that play a significant role in the history or cultural traditions of a group of people. CR include artifacts left by prehistoric aboriginal peoples and those of historical significance. Archaeological constituents, the basic units of archaeological analysis, consist of artifacts and features. Artifacts include carved objects, pottery and ceramics, flaked and ground stones, faunal and floral remains, glass, and metal. Features include earthen works, rock art (e.g., petroglyphs and pictographs), midden soils, and structures (e.g., buildings, monuments, etc). CR are at risk of being damaged by wildfires as well as active natural resource management. In many countries, the United States included, managers have legal requirements to protect CR during fuels treatment and restoration activities as well as during wildfire suppression and post-fire rehabilitation. The successful implementation of prescribed burning and wildfire suppression in CR sensitive areas requires integration of CR and wildland fire science. Knowledge of the local archaeology, artifact materials, site types, and context is essential to minimizing the negative impacts of all management activities. It takes skill and attention to detail to manage fuels and fire CR sensitive areas.

Knowledge of fire behavior, fuel consumption, and fire temperatures can be integrated with information about the temperature sensitivity of various artifact materials. This, coupled with knowledge about the location of artifacts provides guidance on potential adverse effects. This paper reviews literature on the effects of fire on CR, provides guidance on minimizing impacts to CR, and identifies research needs. The review is based primarily on the North American experience but the principles apply universally. Damage increases to CR that are exposed above-ground or on the surface as surface fire intensity increases. Damage to subsurface CR increases with increasing duration and depth of burn. The severity of fire effects then is a function of the material type, the location of the material, fire intensity and depth of burn. Models are available to guide prescription development and wildfire vs. prescribed fire tradeoff analysis. Research to improve our ability to predict fires' temperature histories and material susceptibility would improve our ability to manage the effects of fire on CR.

Keywords: archaeology, cultural resources, fire effects, fire severity, prescribed fire, wildfire

1. Background

Historical and prehistorical peoples left numerous material signs of their presence in the form of habitation structures, monuments, and ceremonial grounds, pictographs and petroglyphs; tools and utensils of daily living, weapons of war; and the bones of the hunt and their own celestial demise, all of which are a part of the human story. Cultural resources (CR) refer to the physical evidence of human occupations which archaeologist use to reconstruct this story. CR includes the objects, locations, and landscapes that play a significant role in the history or cultural traditions of a group of people. These include artifacts left by prehistoric aboriginal peoples and those of historical significance such as the constructions and trappings of explorers, pioneers, and prominent historical figures. CR also include the landscapes and natural features that figure prominently in the mythology, religion, or history of a people. Cultural resource sites may range from lithic scatters from stone-age tool-making sites, to remnants of villages or major population centers, to battlefields, to famous landmarks. Artifacts in contrast refer to objects found either at sites or to those found scattered across the landscape such as tools, weapons, and bones. Fire and resource managers have a moral, and often legal, obligation to protect and preserve CR for their scientific, spiritual, and aesthetic values to this and future generations.

Fire is a natural component of earth's ecosystems. Fire has impacted most of the world's vegetated landscapes having left evidence of its passing in trees, soils, fossils, and cultural artifacts of past civilizations (Scott 2000; Nevle and Bird 2008; Swetnam and Anderson 2008; Pausas and Keeley 2009). With the prevalence of fire many ecosystems have evolved with fire and require periodic fire to maintain species composition, structure and function. The desire to use prescribed burning to treat fuels or restore ecosystems is leading to increased potential for fire to damage CR. Likewise, the recent increase in wildfires and the prospect of more fires implied by climate change scenarios (Running 2008) increases the potential for fire damage to CR. Managers need better tools for evaluating the potential impacts and analyzing trade-offs.

In the United States laws have been passed that require managers to actively protect CR. As early as 1906 the American Antiquities Act empowered the President to set aside and protect federal lands to minimize the loss of CR, primarily prehistoric Indian ruins and artifacts on federal lands in the West. The 1966 National Historic Preservation Act, a hallmark of historic preservation, led to clear definition of, and stringent procedures for, identifying and protecting CR. Under this law land managers have strict processes and procedures for minimizing CR damage in all their activities. It is therefore important that fire managers know how and when to involve archaeologists and CR specialists in planning and implementing management whether on prescribed fire or wildfire. In order for them to be effective they need to be able to communicate consequences to CR specialists. In order for CR specialists to communicate effectively with fire managers and evaluate trade-offs between prospective actions they need a modest understanding of fuels and fire behavior. It is in this context that the author has been involved with CR specialists in the design and implementation of a US National Park Service training course and a rigorous review and synthesis of the effects of fire on cultural resources (Ryan et al., in press).

2. Purpose

The purpose of this paper is to provide cultural resource specialists with a primer on fuels and fire to encourage them to learn more about the role and use of fire in land management and enable them to work more effectively with fire managers in developing

fuel treatment and restoration plans, managing wildfires, and conducting post-fire rehabilitation. Likewise the goal is to provide fire managers with a primer on CR to enable them to work more effectively with CR specialists. This paper draws heavily on a major review and synthesis currently underway (Ryan et al., in press) and previous work (De Bano et al. 1998; Neary et al. 2005, Buenger 2003). The synthesis (Ryan et al., in press) provides a scientific foundation for predicting the potential impacts of fire on cultural resources. It also defines terms and concepts and identifies their practical implications to cultural resources. Prescribed fire and wildfire conditions associated with damage to cultural resources are discussed, as is the need to integrate planning measures to mitigate fire's effects.

3. Effects of Fire on Cultural Resources

The direct effects of fire on archaeological materials result from either energy transported from the burning fuel to the material artifact, or structure, or from the deposition of combustion byproducts on the CR. Direct, first-order fire effects result from the physical or chemical effects of elevated temperature on artifacts or structures, or the degradation of surface characteristics by deposition of combustion-based residues (e.g., tars and soot). Thermal effects vary depending on the type of material (e.g., lithics, ceramics, organic remains, metals, etc.), the physical chemistry of the material (e.g., sandstone vs. obsidian lithics or terracotta pottery vs. porcelain ceramics), the artifact's location (provenience) with respect to the fuels burned, fire behavior and heat transfer. Heating can affect archaeomagnetic (AM), thermoluminescence (TL), and obsidian hydration (OH) dating techniques (Buenger 2003). Direct thermal effects include combustion of organics, including organic objects (pollen, seeds, wood, baskets, hides, etc.), organic paints and dyes used in the manufacture of objects, organic food residues (blood, proteins), or residues and organic substances embedded in composite materials. Fire also consumes and redistributes organic materials with potential impacts on radiocarbon dating and the ability to identify micro-and macro-fossils, proteins, and other organic diagnostics (Buenger 2003). Thermal stress associated rapid temperature increase can physically damage artifacts resulting in shattering fracturing, spalling, crazing, cracking, etc, depending on the material type, e.g., glass, lithic, ceramic, *et cetera*.

Second-order or indirect effects include post-fire damage caused by increased weathering, erosion, and redistribution. Accelerated post-fire erosion can either wash-away, bury or redistribute archaeological materials. The physical redistribution of CR in space along with thermal impacts on dating techniques confounds archaeological interpretation. To assess the potential for second-order effects requires multidisciplinary integration of the archaeology, geology, climatology, and fire severity.

Third-order effects include the human response to fire. Fire suppression activities, particularly scouting and line construction can cause mechanical damage to artifacts and structures. Fire retardants, foam and water can cause chemical damage to surfaces and rapid quenching of heated materials can lead to fractures. In the case of wildland fire it often occurs that unknown sites and artifacts are discovered due to the removal of vegetation. In the absence of protection this can lead to increased vandalism.

The remainder of this paper will focus on understanding first-order fire effects.

Knowledge of fuels, fire behavior, and heat transfer can be used to predict and manage fire's effects on varying artifacts types, sites, and landscapes. This knowledge can

also be used to assess tradeoffs between the effects of wildfires vs. treatments, plan post-fire archaeological surveys, or evaluate rehabilitation and stabilization needs. Fires burn throughout a range of intensities from smoldering flameless fires producing little if any smoke to creeping fires with short, thin flames to raging crown fires with walls of flames 50 meters high or more (Ryan 2002) (Table 1). The duration of a fire's passing may be as short as a minute in the case of a fast moving surface or crown fire, or as long as a day in a smoldering ground fire. As fires burn throughout this range of intensities and durations the impact on the environment and the cultural resources therein varies tremendously.

Table 1 Fire behavior characteristics for ground, surface, and crown fires (from Ryan 2002)¹.

Fire type	Dominant Combustion Phase	General Description	Rate of Spread (meters/minutes)	Flame Length (meters)	Fireline Intensity (kW/meter)
Ground	Smoldering	Creeping	3.3E-4 to 1.6E-2	0.0	<10
Surface	Flaming	Creeping	<3.0E-1	0.1-0.5	1.7E0-5.8E1
		Active/Spreading	3.0E-1 to 8.3E0	0.5-1.5	5.8E1-6.3E2
		Intense/ Running	8.3E0-5.0E1	1.5 to 3.0	6.3E2 to 2.8E3
Transition	Flaming	Passive Crowning	Variable ¹	3.0 to 10.0	Variable ¹
Crowning	Flaming	Active Crowning	1.5E1 to 1.0E2	5.0 to 15 ²	1.0E4 to 1.0E5
		Independent Crowning	Up to ca. 2.0E2	Up to ca.70 ²	Up to ca. 2.7E6

¹ Rates of spread, flame length and fireline intensity vary widely in transitional fires. In subalpine and boreal fuels it is common for surface fires to creep slowly until they encounter conifer branches near the ground, then individual trees or clumps of trees torch sending embers ahead of the main fire. These embers start new fires, which creep until they encounter trees, which then torch. In contrast, as surface fires become more intense, torching commonly occurs prior to onset of active crowning.

² Flame lengths are highly variable in crown fires. They commonly range from 0.5 to 2 times canopy height. Fire managers commonly report much higher flames but these are difficult to verify or model. Such extreme fires are unlikely to result in additional fire effects within a stand but are commonly associated with large patches of continuous severe burning.

Much of field archaeology is a descriptive science. Archaeologists have coined a wide array of terms to describe their observed effects of fire on CR materials. Terms vary depending on the physical and chemical properties of the artifact and how they respond to the temperatures reached, the duration of high temperatures, or the deposition of combustion byproducts. Thermally induced color changes, weight loss, stress fractures, and changes in mineralogy are commonly described. Stress fractures are described in such terms as: thermally induced enhancement of existing cracks, thermal cracks, spalling, and potlidding of lithics, and delamination of shell specimens. Fading or combustion of paints and pigments; deposition of soot, tars, resins, etc.; increases or decreases in luster or sheen; melting, deformation, and vesiculation (obsidian); and calcination of bones are commonly noted fire effects. A handful of laboratory experiments have been conducted to better understand the field observations (Bennett and Kunzman 1985, Buenger 2003).

Literature review (Buenger 2003, Ryan et al, in press) provides a perspective on the range of temperatures associated with varying effects (Table 2). These data indicate a wide range of potential effects depending on the physical composition of the various artifact types. These temperatures are well within the range of temperatures associated with the various stages of combustion in a wildland fire (Table 3). Temperature ranges associated with damage to CR materials were derived from laboratory studies (Bennett and Kunzman 1985, Buenger2003, see Buenger 2003 for review).

It is common knowledge that many material transitions occur as complex functions of temperature and duration of exposure. Such functions are often described by Arrhenius functions (Figure 1). Few time-temperature data are available and those that do exist are not robust enough to calculate actual Arrhenius functions but they are adequate to illustrate

their potential use. Given estimates of the Arrhenius functions for various materials provides a means to compare expected temperatures and durations of fires to assess the

Table 2 Thermal effects to various cultural resource materials¹.

Cultural Resource		Temperature	Effect
Ceramic Materials		350	Organic paint begins to burn off
		400	TL readings altered
		750-870	Spalling, quicklime formation
Lithic Materials	Chert	150	Impurities and possible fractures
		121-400	Interior luster changes
		350-400	Distortion, brittleness, explosiveness
		240-800	External surface color change
		600-800	Optical dulling of external surface
	Obsidian	300	Hydration band diffused
		500+	Hydration band not present
		540	Crazing
		760	Vesiculation
		700-800	Melting
	Basalt	300-600	Spalling, Fracturing
		100-800	Weight Loss
	Quartz	>573	Blackening, thermal expansion, crystalline structure changed
	Ground Stone	300+	Smudging, organic materials present begin to diminish-pollen
		800+	Organic material diminished-animal proteins
Rock Art Resources		High heat	Exfoliation, blackening
Subsurface Materials	Ground Stone	300	Spalling, cracking
	Bone	300	Spalling, charring
		400	Chalking
		500	Severe chalking
		800	Frothing

¹ Rate and duration of heat change may be more critical for determined effect than the absolute temperature reached. Rapid heating or cooling may cause spalling, cracking, or fracturing at lower temperatures.

Table 3 Temperatures associated with combustion phases in wildland fuels.

Temperature °C	Effect
0-100	Preheating of fuel: free water is evaporates
100-200	Preheating of fuel: bound water and low molecular weight compounds volatilized, decomposition of cellulose (pyrolysis) begins, solid fuel is converted into gaseous vapors
200-300	Preheating of fuel: thermal degradation continues more rapidly
300-325	Ignition temperature in well aerated wildland fuels: transition to flaming
325-400	Flaming phase: rapid increase in decomposition of solid fuel
400-500	Flaming phase: gas production rate peaks around 400°C and declines between 450°C and 500°C as all residual volatile compounds are released.
500-1000	Flaming phase: Mass flame temperatures within flames may approach 1600°C in deep flame envelopes but temperatures of 500°C to 1000°C are more typical
500-800	Glowing phase: residual carbonaceous fuel (charcoal) burns by glowing combustion. The combustion of charcoal is associated with the liberation of CO and CO ₂

likelihood of CR damage. Such assessments require applying knowledge of the CR material type and its location, for example exposed above ground vs. insulated by unburnable mineral soil, the combustion characteristics of nearby fuels, and the heat transfer mechanisms coupling fire behavior to the CR. Cabins and similar woody structures may be ignited from embers at some distance from a fire. However, the primary mechanisms for transferring heat from the fire to the CR are radiation, convection, and conduction. Radiation, the transfer of energy through space, nominally decreases with the square of the distance between the flames and the CR. Large flames emit more radiation and thus can more effectively heat artifacts and structures at a distance, but even large flames cannot damagingly heat CR materials beyond about 30 meters (Ryan et al., in press). Convection,

the transfer of energy through moving particles from hot to cool, as manifested in pulsating flames and billowing smoke is a very efficient means of transferring energy from the burning fuel to CR but the convection column is rapidly cooled by the entrainment of

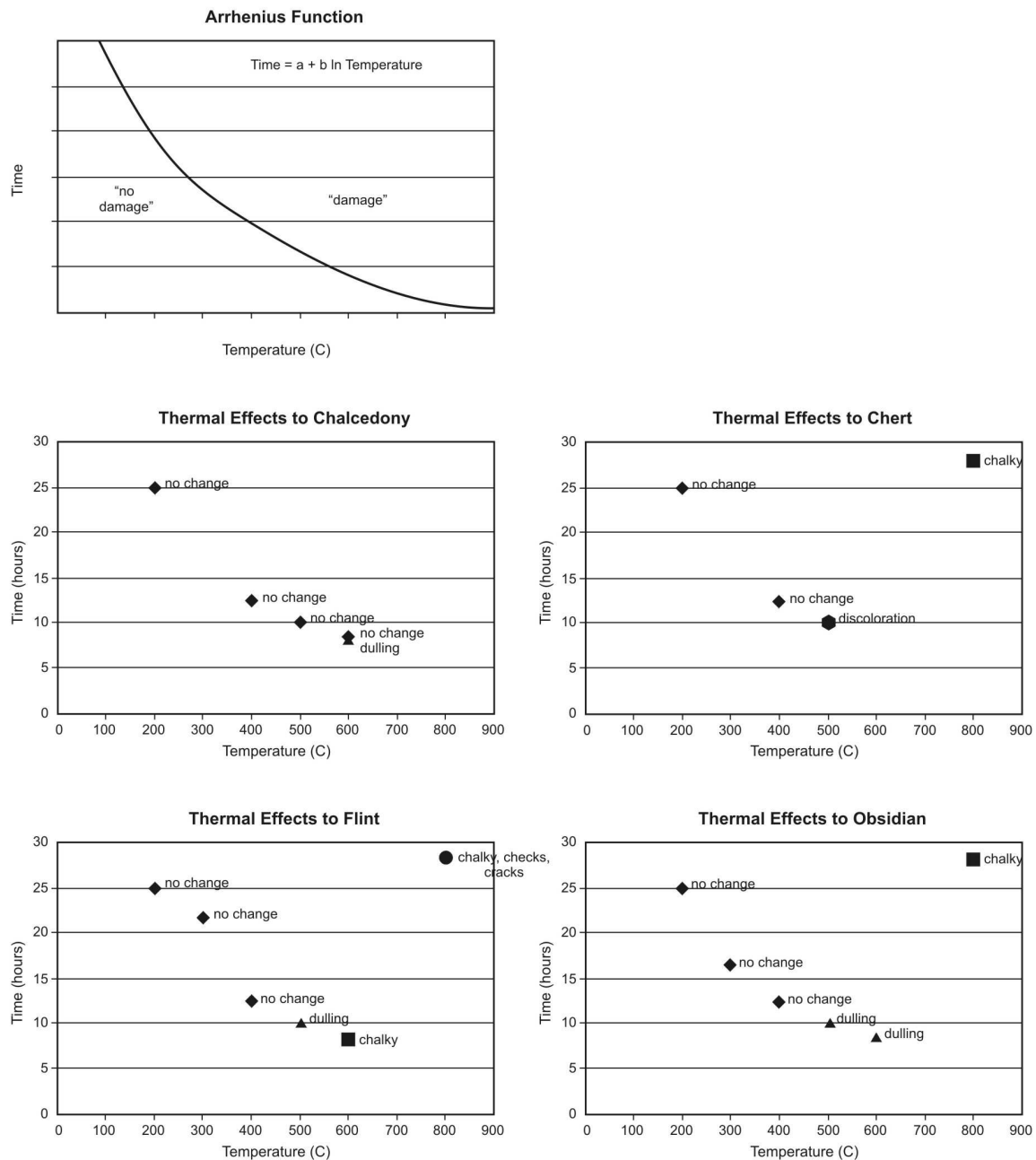


Figure 1 A hypothetical Arrhenius function describing the time-temperature relationship resulting in damage (top) and examples for four lithic artifact materials (Bennett and Kunzman 1985, Deal, in press).

ambient air. Radiation and convection are the primary mechanisms for heating exposed surface and above ground CR. For radiation and convection to effectively heat CR the CR must be relatively close to the combustion zone. Conduction, the transfer of energy through solids is the primary mechanism for heating subsurface CR. The fire environment consisting of the vegetation/fuels, terrain and weather, along with the ignition pattern determine fire severity. Large uniform fire environments lead to large uniform fires.

However, in most wildland areas fuels are spatially variable. It is the juxtaposition of the artifacts to a specific fire environment that determines the direct effects of fire on CR.

4. Fire Severity

When assessing potential for CR fire-damage the primary considerations are the types of fuel present, their moisture content, and wind. Fire intensity is determined by the mass of fine fuels (FF) in the surface and canopy strata and how rapidly they are ignited. The rate of ignition is primarily determined by FF moisture content and wind velocity. However, FF burn out quickly and are incapable of sustaining long duration burning. Thus, fire's potential impacts on above-ground artifacts and structures is a function of the mass of fine fuels, short term weather (humidity and wind) and how the fuels are ignited, e.g., heading fire vs. backing fire. In contrast subsurface CR are primarily impacted by the conduction of heat through the soil which is a function of the soil type, its moisture content, and the duration of burning (Campbell et al. 1994, 1995). Coarse woody debris (CWD) and duff/leaf mold (fermentation and humus layers) are capable of sustained burning at low moisture contents which only occur after extended drying.

Fires burn in varying combinations of ground, surface, and crown depending on the local conditions at the specific time a fire passes a point. Changes in surface and ground fire behavior occur in response to subtle changes in the microenvironment, stand structure, and weather leading to a mosaic of fire treatments at multiple scales in the ground, surface and, canopy strata. Crown fires exhibit high intensity (energy release rate) and of short duration. Ground fires are of low intensity and long duration. Surface fires are intermediate to crown and ground fires and cover a wide range of intensities and duration depending on the amount of available fuel loading and its size distribution. Heavy concentrations of CWD can result in long duration high intensity heating of the soil. Correspondingly, the greatest damage to subsurface CR occurs under these localized hot spots. However, such concentrations typically cover only a small proportion of the surface of the ground, rarely more than 10 percent, even at very high fuel loadings (Albini 1976; Peterson and Ryan 1986, Brown et al. 2003). In most forests either duff or peat covers a much greater proportion of the surface than FWD and CWD combined. The burnout of these organic soil horizons by smoldering combustion is the primary source of mineral soil heating. During crown fires and surface fires the majority of heat released by combustion is transferred to the atmosphere and surrounding exposed surfaces by radiation and convection. During ground fires much of heat released is transferred into the soil by conduction. When fire moves through the crown alone (independent crown fire, see Table 1), there is often only a modest effect to surface objects and none to subsurface artifacts because of the short burning duration of canopy fuels (Figure 2). During glowing and smoldering combustion of surface and ground fuels, residence time is prolonged and the soil is more deeply heated (Figure 2). Once ignited by the passage of a surface fire, dry forest duff greater than about 4 cm deep can burn independently without continued flaming in surface fuels. The duration of smoldering can then range from as little as two hours to more than 30 hours in deep organic soil horizons (Hungerford et al. 1995; Reardon et al. 2007; Grishin et al. 2009). Given longer durations heat may penetrate deeply into the soil profile. When crown fires or intense surface fires occur over dry duff, smoldering fire can continue to burn for several hours after the passage of the flaming front leading to high heat release both above and below ground. Such conditions, i.e., high intensity and long duration, cause the greatest

direct, first-order fire effects on CR and create the most favorable conditions for second-order effects (erosion, weathering and redistribution). The term commonly used to describe the degree to which surface and ground fuels are consumed is “depth of burn.”

Temperature Effects on Cultural Resources

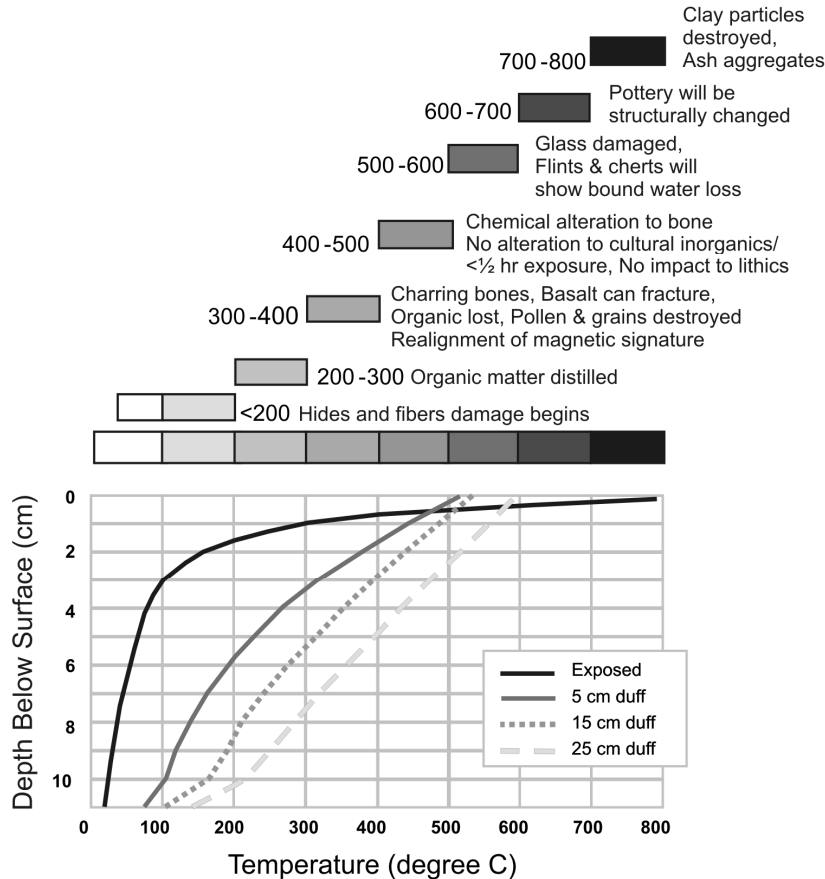


Figure 2.. Potential impacts of fire on various CR materials. Temperature ranges associated with various fire effects to cultural resource materials (top) compared to the depth of heat penetration into mineral soil (bottom). Depth of heat penetration is for a crown fire over exposed mineral soil (observed in jack pine *Pinus banksiana* in the Canadian Northwest Territories) or for ground fire burning in 5-, 15-, and 25-cm of duff (predicted depth of heat penetration via Campbell et al.1994, 1995). Observed or predicted are based on coarse dry soil, which provides the best heat conduction (i.e., a worst-case scenario) (Adapted from Ryan 2002). The figure can be used to project the depth at which various fire effects may be expected from various fires.

In forests with long fire return intervals the buildup of duff covers most of the forest floor surface and the most common source of deep soil heating is the burnout of the duff. In short fire return forests where duff accumulation is minimal and typically restricted to duff mounds beneath tree canopies, the burnout of CWD is the primary source of deep soil heating. Equations exist to predict duff consumption in the United States (Ottmar et al. 2005; Reinhardt et al. 1997) and Canada (Chrosociewicz 1968, 1978a, b; Van Wagner 1972; de Groot et al. 2009).

In addition to the burnout of duff and woody fuels there are a number of means by which buried cultural resources can be heated. One of the most common is the burnout of stumps and dead roots. Commonly at cultural sites logs and building materials are buried or partially buried. Once ignited these burn slowly, deeply heating lower layers in the soil profile. Another mode of subsurface heating is when soil is interspersed with organic material in old middens and dump sites where fire can freely move throughout the strata.

Following a fire, researchers are able to better understand fire dynamics by quantifying the depth of burning into the ground (Ryan and Noste 1985; De Bano et al. 1998; Jain et al. 2008) and consumption and depth of char in FWD and CWD (Albini and Reinhardt 1995, 1997). When depth of burn/char measurements are coupled with estimates of flame length and fire spread direction it is possible to recreate fire's movement through an area. By combining flame length and depth of burn/char measurements, researchers are able to create a two-dimensional matrix of fire severity. For example, Ryan and Noste (1985) assessed the effects of fire to tree crowns and ground fuels by visiting burned sites and measuring scorch heights and using them to back-calculate fire line intensity by using Van Wagner's (1973, 1977) crown scorch model. Depth of burn/char measurements can be used to estimate residence time in surface fuels and soils. Wildland fuels are poor conductors of heat. Due to heat transfer constraints fuels burn at relatively constant rates (Anderson 1969, Frandsen 1991). A fire can be very intense as exhibited by long flame lengths but its duration within the forest strata most determines the depth of burn/char. For further discussion on the topic of fire intensity vs. fire severity readers are referred to the recent review by Keeley (2009). A more in-depth discussion of the differences between fire intensity and fire severity can be found in Neary et al. (2005) and Ryan (2002). Field guidance on determining fire severity may also be found in Ryan et al. (in press).

The literature on depth of burn has been previously reviewed (Ryan and Noste 1985, DeBano et al. 1998, Ryan 2002, Neary et al. 2005, Keeley 2009). The following depth of burn classes have been found useful for describing the effects of fire on plants and soil resources as they reflect increasing levels of soil heating:

- *Unburned:* Plant parts are green and unaltered, there is no direct effect from heat.
- *Scorched:* Fire did not burn the area but radiated or convected heat caused visible damage. Mosses and leaves are brown or yellow but species characteristics are still identifiable. Soil heating is negligible.
- *Light:* In forests the surface litter, mosses, and herbaceous plants are charred to consumed but the underlying forest duff or organic soil is unaltered. Fine dead twigs are charred or consumed but larger branches remain. Logs may be blackened but are not deeply charred except where two logs cross. Leaves of understory shrubs and trees are charred or consumed but fine twigs and branches remain. In non-forest vegetation plants are similarly charred or consumed, herbaceous plant bases are not deeply burned and are still identifiable, and charring of the mineral soil is limited to a few millimeters.
- *Moderate:* In forests the surface litter, mosses, and herbaceous plants are consumed. Shallow duff layers are completely consumed and charring occurs in the top centimeter of the mineral soil. Where deep duff layers or organic soils occur they are deeply burned to completely consumed resulting in deep charcoal and ash deposits but the texture and structure of the underlying mineral soil are not visibly altered. Leaves of shrubs and fine dead twigs are completely consumed, larger branches and rotten logs are mostly consumed, and logs are deeply charred. Burned-out stump holes and rodent middens are common. Shrub stems frequently burn off at the base during the ground fire phase leaving toppled residual aerial stems, that were not consumed in the flaming phase, lying on the ground. In non-forest vegetation plants are similarly consumed, herbaceous plant bases are deeply burned and unidentifiable. In shrublands charring of the mineral soil is on the order of 1.0 centimeter but soil texture and structure are not clearly altered.

- *Deep:* In forests growing on mineral soil the surface litter, mosses, herbaceous plants, shrubs, and woody branches are completely consumed. Sound logs are consumed or deeply charred. Rotten logs and stumps are consumed. The top layer of the mineral soil is visibly oxidized, reddish to yellow. Surface soil texture is altered and in extreme cases fusion of particles occurs. A black band of charred organic matter 1 to 2 centimeters thick occurs at variable depths below the surface. The depth of this band is an indication of the duration of extreme heating. The temperatures associated with oxidized mineral soil are associated with flaming rather than smoldering. Thus, deep depth of burn typically only occurs where woody fuels burn for extended duration such as beneath individual logs, in concentrations of woody debris, or around burned-out stump holes.

5. Managing fire Effects

Managing fire effects during prescribed burning requires specifying acceptable fire environment characteristics and ignition pattern to control the intensity and duration of burning. Figure 3 illustrates the influence of duff moisture content on duff consumption. High duff moisture content provides the maximum protection for surface and sub-surface CR. However, minimizing duff consumption during a prescribed burn may not meet other resource objectives and may leave undesirable fuel loadings for a subsequent wildfire. If such fire occurs under dry duff conditions maximum soil heating and damage to surface and sub-surface CR can be expected.

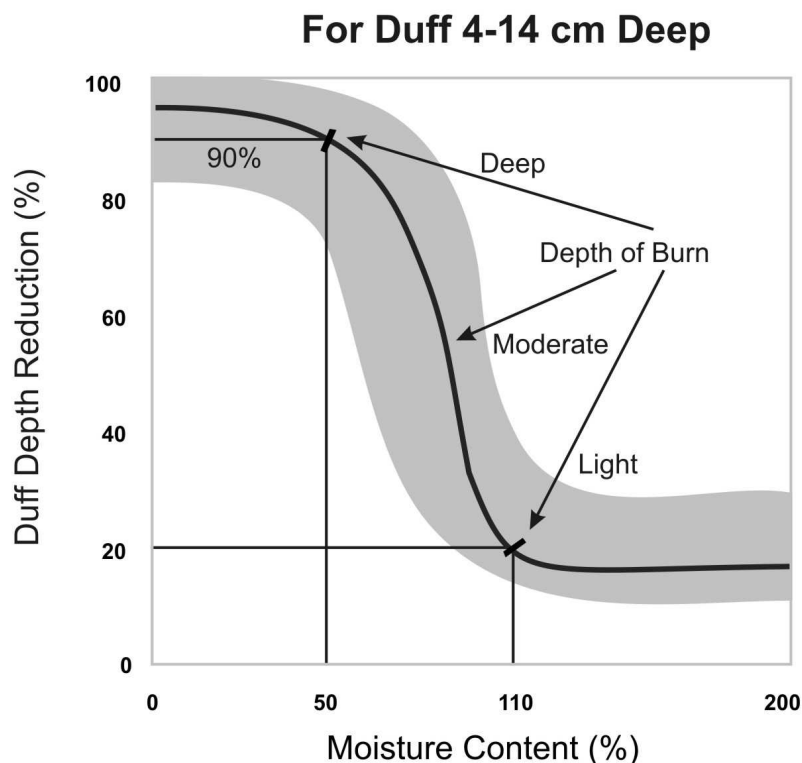


Figure 3 Depth of burn varies with duff moisture content (from FOFEM, [www. Firelab.org](http://www.Firelab.org)). Shaded area illustrates the range encountered as local variations occur depending on the intensity and duration of burning in surface fuels

Managing the effects of fire on CR is an interdisciplinary endeavor. The more familiar CR specialists are with the local site characteristics and artifact types and materials, the better they will be prepared to collaborate with fire managers. Above ground resources such as structures and rock art (pictographs and petroglyphs) may be exposed to intense heating from intense surface fires and crown fires, i.e., common wildfire conditions. It is important to carefully treat fuels and vegetation around such resources to minimize their exposure. Careful selection of prescribed burning conditions and careful management of ignition patterns can minimize, but not preclude damage to these resources, and manual removal of fuels immediately surrounding such resources may be necessary. Prior knowledge about the typical density and depth of subsurface CR is very valuable for projecting the potential for significant impacts on these resources. The past history of disturbance, whether previous fires, frost heaving, animal or human damage, and tree-fall often so confounds archaeological diagnostics that CR specialists do not rely heavily on surface materials for interpretations, rather they remove a variable amount of surface materials prior to rigorous study. Most of the direct effects of fire occur in the surface few centimeters (Figure 2), where artifacts often have limited value. Further, not all observable changes affect archaeological interpretation (Table 2). Aesthetic changes to the surface of an artifact may not limit its archaeological value. For example, luster changes may not affect the correct description of a tool or sooting may not adversely affect identification of an earthen pot. When assessing the costs and benefits of fuel treatment and restoration projects it is important to have realistic expectations of the potential for resource damage under the various options, e.g., prescribed fire vs. wildfire. Careful selection of prescription parameters to control surface fire intensity and depth of burn (Figure 3) will minimize the potential damage to above- and below-ground cultural resources.

The state of the pre-burn fuels and weather are highly variable both spatially and temporally. It is this variability that most limits our ability to predict a fire's effects on cultural resources. Thus it is desirable to have local fuels and weather data when planning, implementing, monitoring and reconstructing a fire. In the case of wildfire, pre-burn conditions often must be inferred from post-fire proxy data, for example inferring pre-burn conditions from those in a "similar" near-by unburned area. Predicting fire behavior and understanding its effects requires knowledge of the fire environment, heat transfer principles, the responses of various artifact materials to heat, and to a lesser extent, the chemicals released by fire, such as ash or smoke, or those used in fire suppression, such as retardants or foams. Tools exist to predict fire behavior (Andrews 2008; Finney 1998; Hirsch 1996) and its effects (Reinhardt et al. 1997; Ottmar et al. 2005) through interpreting weather and fuel conditions. It is important for managers to recognize some factors cannot be controlled. There will always be spatial variation, adverse environmental conditions, and complex vegetative structures that make prescription development an inexact science. As we gain a better understanding of the effects of fire on cultural resources, we must take appropriate action to reduce and manage risk to these assets.

6. Conclusions

As is often the case in interdisciplinary endeavors such as fire-archaeology a lack of consistent terminology, disparate methods, and conflicting goals impede fully successful integration. Much of the literature on the effects of fire and fire management activities on CR comes from *ex post facto* field studies on wildfires. These studies are conducted by

archaeologists with only a modest understanding of fire behavior and heat transfer principles and minimal data on pre-fire fuels and actual burning conditions during the fire. The data are observational and informative but often lack repeatable or quantitative description. There is often a lack of specific description of the criteria used to measure fire effects. Thus there is ambiguity in the fire environment, fire behavior, and the observed CR effects. The limited number of controlled laboratory and prescribed burning field studies often lack realism, thus making inferences tenuous. Field trials need more stringent methods for reporting fuel and fire conditions as well as more rigorously documented temperature histories, fuel consumption and fire severity observations from the proximate site wherein the effects are observed. These shortcomings suggest the need for additional research. Despite these shortcomings it is possible to bound fire management-CR effects problems by integrating across the fire science and CR disciplines. Such integration can minimize the negative effects of fire management activities on CR and maximize the opportunity to actively manage fuels and vegetation to meet other social values without compromising CR values.

7. Acknowledgements

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